Future Accelerator Challenges in Support of High-Energy Physics

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Introduction

- Historically, HEP has depended on advances in accelerator design to make scientific progress
  - cyclotron → synchrocyclotron → synchrotron → collider (circular, linear)
- Advances in accelerator design and performance require corresponding advances in accelerator technology
  - magnets, vacuum systems, RF systems, diagnostics, ...
- Accelerators enable the study of particle physics phenomena under (more or less) controlled conditions
- Cost of today's accelerator projects is high
  - international cooperation and collaboration are no longer optional
  - there is a danger of "pricing ourselves out of the market"

Accelerator Deliverables

- Particle accelerators are designed to deliver two parameters to the HEP user
  - energy and luminosity

- Energy is by far the easier parameter to deliver
  - and is easier to accommodate by the experimenters
    - higher luminosity invariably presents challenges to the detector
      - ...and to the accelerator physicist!

- Luminosity is a measure of collision rate per unit area
  - event rate for a given event probability ("cross section") is given by

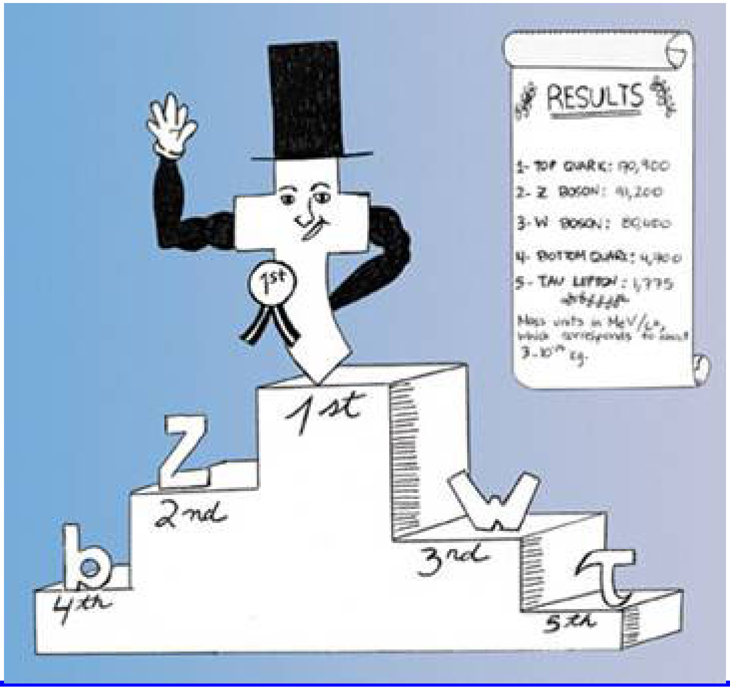
$$R = \mathscr{L}\sigma$$

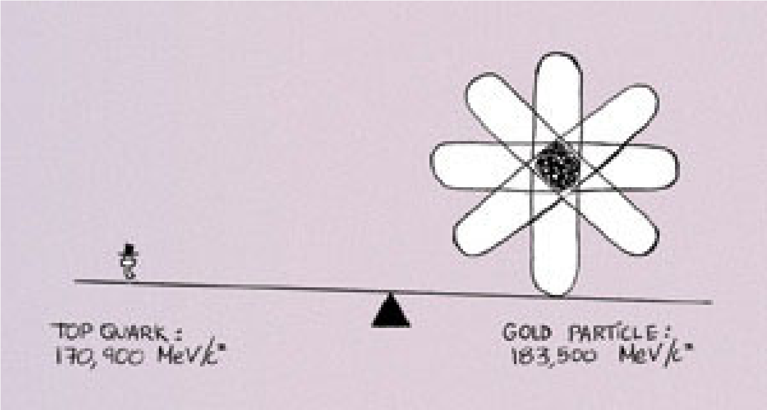
- For a collider with equal beam sizes at the IP, luminosity is given by $\frac{N_+ N_- f_c}{4\pi \sigma_x^* \sigma_y^*}$

⇒ Need intense beams and small beam sizes at IP

Particle Physics Questions (1)

- **There are two primary accelerator-related thrusts**
  - **understanding the origins of mass**
    - **what gives particles such different masses?**
      - **top quark has mass comparable to Au nucleus**
      - **neutrino mass is likely a fraction of an eV**





Particle Physics Questions (2)

- understanding why we live in a matter-dominated universe
  - why are we here?

- After Big Bang, equal amounts of matter and antimatter created
  - why didn't it all annihilate?
    - believed to be due to slight differences in reaction rates between particles and antiparticles
      - charge-conjugation–parity (CP) violation

- CP violation observed experimentally in "quark sector"
  - B factories were built to study this
    - unfortunately, CP violation in quark sector not large enough to explain observed baryon asymmetry
  - prevalent view is that required additional CP violation occurs in lepton sector
    - never observed; neutrinos are the hunting ground

Today's Machines

- High energy physics typically uses colliders (counter-propagating beams that collide at one or more interaction points "IPs")
  - until recently, colliders were single-ring machines that required beams of particles and antiparticles, e.g., e^- and e^+
    - to get higher intensities and more bunches, modern colliders use two rings and thus no longer require two beams that have opposite sign

$$\frac{N_+ N_- f_c}{4\pi \sigma_x^* \sigma_y^*}$$

- Colliders typically store one of two types of particles
  - hadrons (protons, heavier ions)
    - Tevatron $(\mathrm{p}-\bar{\mathrm{p}})$, RHIC (nuclear physics), LHC (p-p)
  - leptons (electrons)
    - CESR-c, PEP-II, KEKB

Today's Machine Limitations (1)

- Hadron colliders
  - protons are composite particles
    - only ≈10% of the beam energy is available for the hard collisions that make new particles
      - need $\mathcal{O}$(10 TeV) collider to probe the 1 TeV mass scale
    - desired high beam energy requires very strong magnets to store and focus beam in a reasonable-sized ring
  - antiprotons difficult to make
    - takes hours to replace them if beam is lost
  - using p-p collisions bypasses the second issue, but not the first
    - the demand for ever-higher luminosity has led the LHC to choose
      - p-p collisions
      - many bunches
      - two separate rings that intersect at select locations

Today's Machine Limitations (2)

- **Lepton colliders (e^-e^+)**
  - synchrotron radiation is the biggest challenge
  - emitted power in circular machine is

$$P_{SR}[\mathrm{kW}] = \frac{88.5\, E^4[\mathrm{GeV}]\, I[\mathrm{A}]}{\rho[\mathrm{m}]}$$

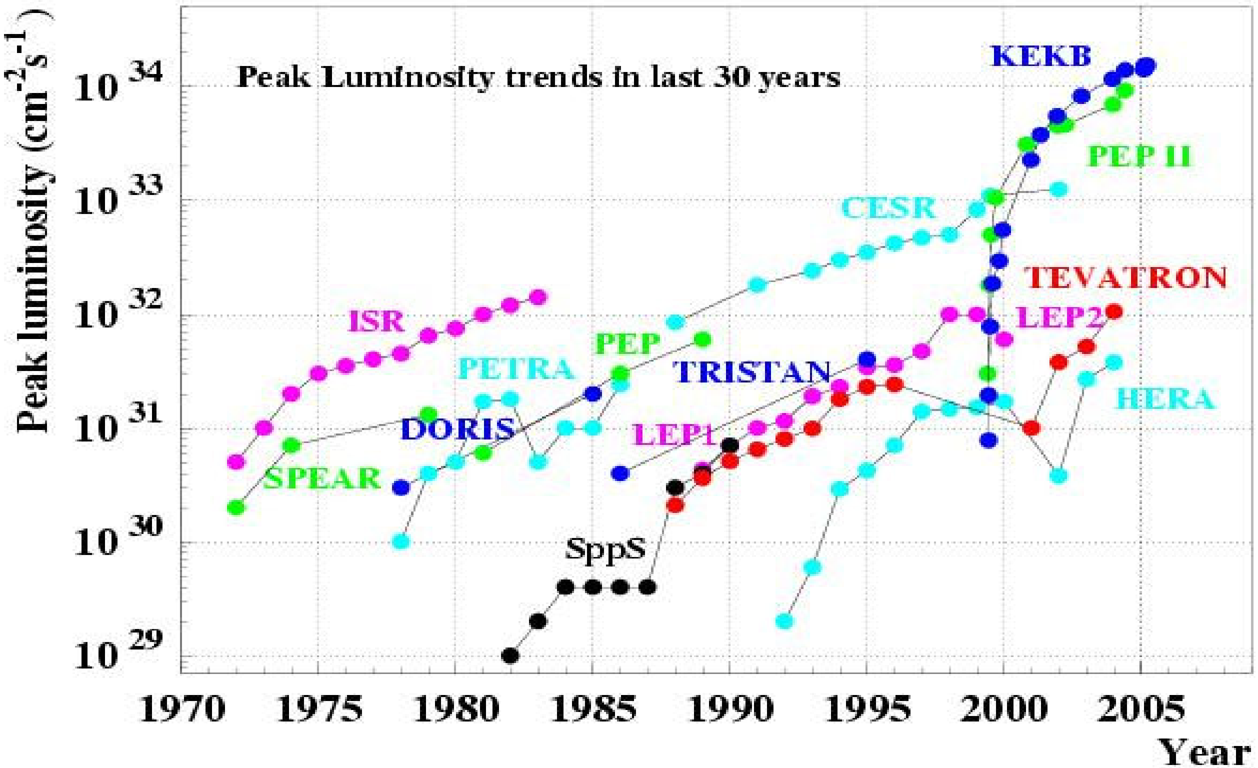
  - for a 1 TeV c.m. collider in the LHC tunnel (C = 27 km) with a 1 mA beam, radiated power would be 2 GW
    - would need to provide this power with RF
    - and remove it from the vacuum chamber!

- **Approach for high energies is linear collider (ILC, CLIC)**
  - footprint is large: 31 km in length (ILC); 48 km in length (CLIC)
    - too big to fit on-site at existing lab
  - single-pass acceleration is inefficient (no reuse of hardware)

Luminosity Performance

- e^+e^- colliders have made great strides in delivering luminosity in recent years
- Both KEKB and PEP-II quickly reached luminosities beyond 1×10^{34} cm^{-2} s^{-1}

New machines likely to be judged in comparison to these standards!



Future Machines

- At present, there are several machines on the drawing board to address the high-priority physics issues
  - not all of these are at the same stage of development
    - ILC and CLIC are furthest along in terms of R&D activities
  - most of these machines are very expensive
    - it is not likely that all of these will be built

- Precision frontier
  - ILC (e^+e^-)
  - Neutrino Factory (μ^+ or μ^-)
  - Super-B Factory (e^+e^-)

- Energy frontier
  - CLIC (e^+e^-)
  - Muon Collider ($\mu^+\mu^-$)

For reasons of personal taste and familiarity, I will tend to emphasize muon machines in this talk; these are the most novel, but not the most advanced, designs

Muon Accelerator Advantages

- **Muon-beam accelerators can address both of the outstanding accelerator-related particle physics questions**
  - **neutrino sector**
    - **Neutrino Factory beam properties**

$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \overline{\nu}_\mu$$

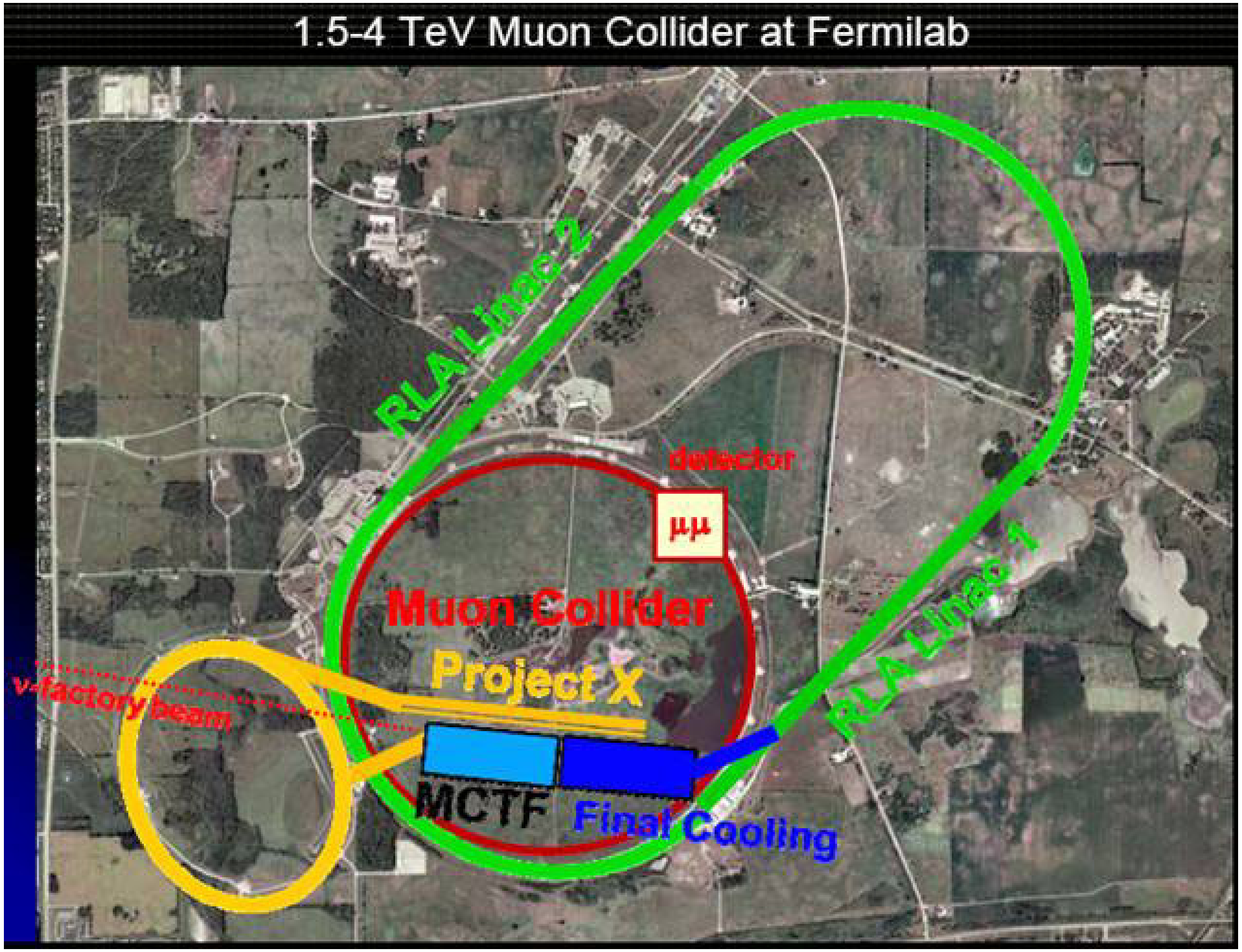
$$\mu^- \to e^- \overline{\nu}_e \nu_\mu \Rightarrow 50\% \overline{\nu}_e + 50\% \nu_\mu$$

Produces high energy neutrinos

    - **decay kinematics well known**
      - **minimal hadronic uncertainties in the spectrum and flux**
    - **$\nu_e \to \nu_\mu$ oscillations give easily detectable "wrong-sign" μ**
  - **energy frontier**
    - **point particle makes full beam energy available for particle production**
      - **couples strongly to Higgs sector**
    - **Muon Collider has almost no synchrotron radiation**
      - **narrow energy spread**
      - **fits on existing Lab sites**

Muon Collider at Fermilab

- **Schematic of Muon Collider on Fermilab site**
  - **it fits comfortably**



Muon Beam Challenges

- **Muons created as tertiary beam ($p \rightarrow \pi \rightarrow \mu$)**
  - low production rate
    - need target that can tolerate multi-MW beam
  - large energy spread and transverse phase space
    - need solenoidal focusing for the low energy portions of the facility
      - solenoids focus in both planes simultaneously
    - need emittance cooling
    - high-acceptance acceleration system and decay ring
- **Muons have short lifetime (2.2 μs at rest)**
  - puts premium on rapid beam manipulations
    - presently untested ionization cooling technique
      - high-gradient RF cavities (in magnetic field)
    - fast acceleration system

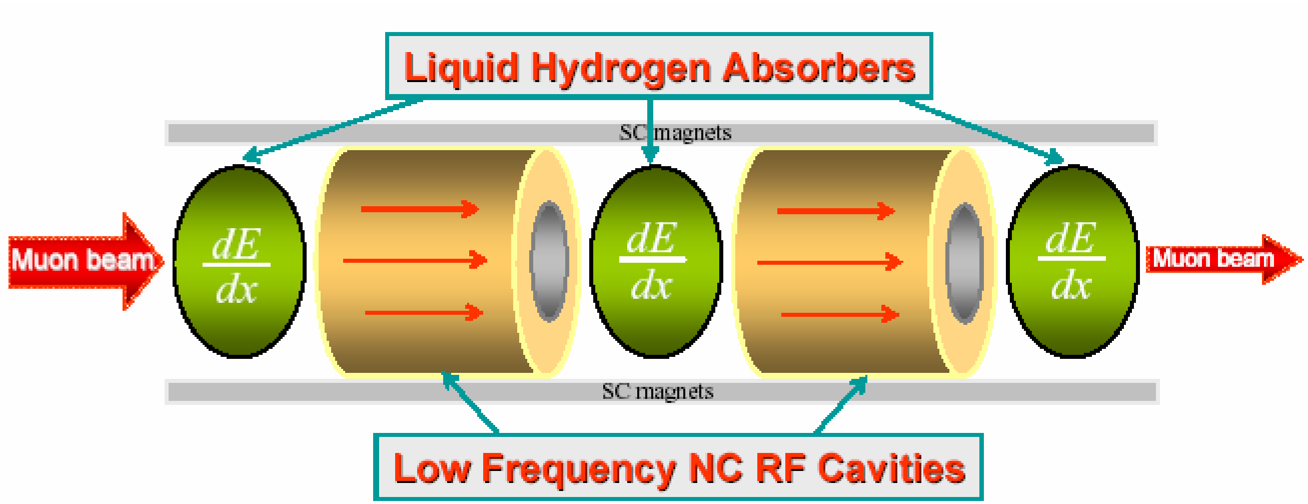
If intense muon beams were easy to produce, we'd already have them!

- **Decay electrons give backgrounds in collider detector and instrumentation, and heat load to magnets (NF and MC)**

Ionization Cooling (1)

- **Ionization cooling analogous to familiar SR damping process in electron storage rings**
  - energy loss (SR or *dE/ds*) reduces p_x, p_y, p_z
  - energy gain (RF cavities) restores only p_z
  - repeating this reduces $p_{x,y}/p_z$ ($\Rightarrow$ 4D cooling)

  - presence of LH_2 near RF cavities is an engineering challenge
    - we get lots of "design help" from Lab safety committees!



Ionization Cooling (2)

- **There is also a heating term**
  - for SR it is quantum excitation
  - for ionization cooling it is multiple scattering

- **Balance between heating and cooling gives equilibrium emittance**

$$\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2}\left|\frac{dE_\mu}{ds}\right|\frac{\varepsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

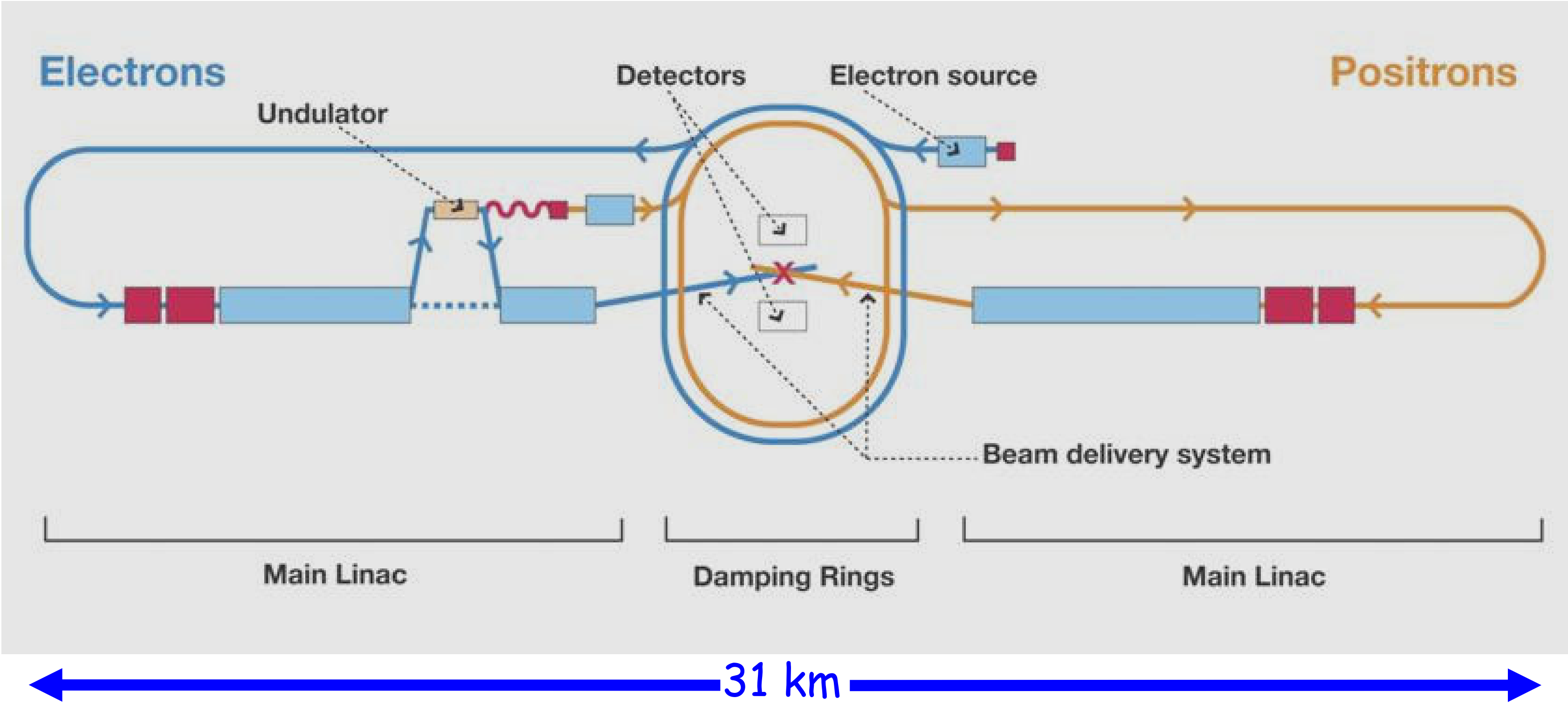
Cooling Heating

$$\varepsilon_{x,N,equil.} = \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta m_\mu X_0 \left|\frac{dE_\mu}{ds}\right|}$$

- prefer low $\beta_\perp$ (strong focusing), large X_0 and dE/ds (H_2 is best)

ILC

- ILC is aimed initially at 0.5 TeV energy scale
  - two linacs + central damping ring complex
    - damping rings produce 2 pm-rad vertical emittance
  - technical challenges: low emittance, SRF gradient (31.5 MV/m)

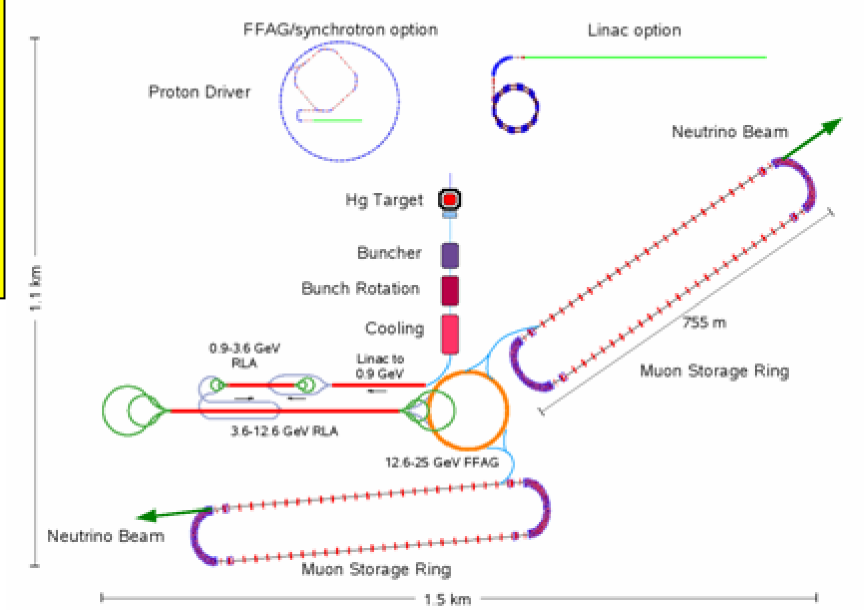


Neutrino Factory

- Neutrino Factory comprises these sections
  - Proton Driver
    - primary beam on production target
  - Target, Capture, and Decay
    - create π; decay into $\mu \Rightarrow$ MERIT
  - Bunching and Phase Rotation
    - reduce ΔE of bunch
  - Cooling
    - reduce transverse emittance $\Rightarrow$ MICE
  - Acceleration
    - 130 MeV $\rightarrow$ 20-50 GeV with RLAs or FFAGs
  - Decay Ring
    - store for 500 turns; long straight(s)

Aim for 10^{21} ν_e per year aimed toward detector(s)

ISS Baseline

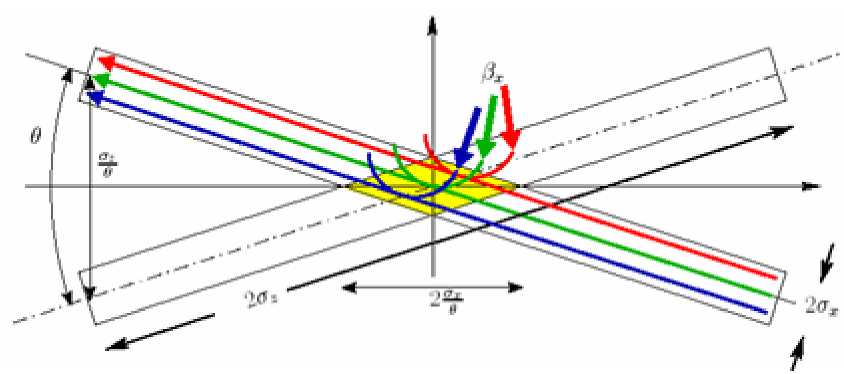


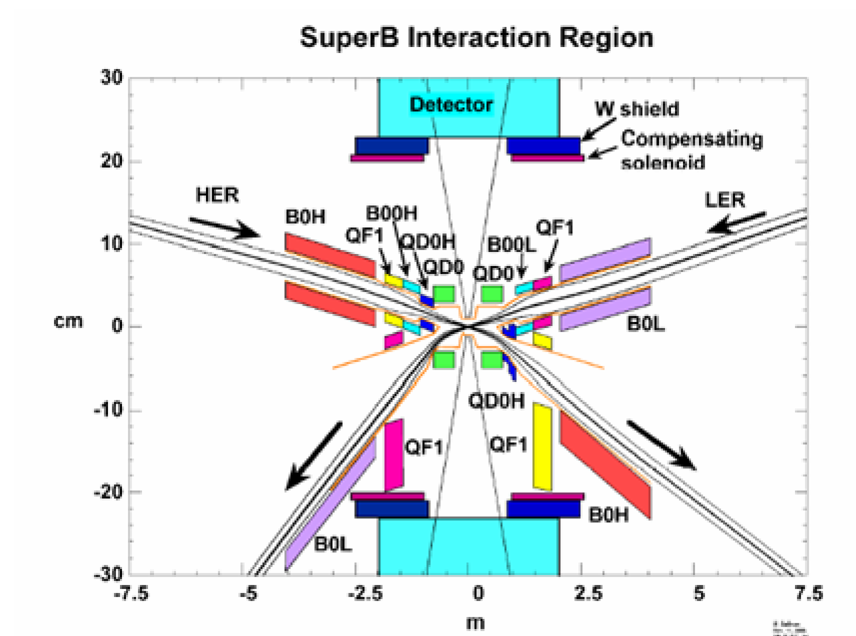
Super-B Factory

- **Goal: run at $\Upsilon(4S)$ with luminosity of ~1×10^{36} cm^{-2} s^{-1}**
- **Use low-emittance rings with "crab waist" scheme to reduce effective beam size at IP**
  - IR sextupoles suppress harmful synchrobetatron resonances

Frascati-SLAC design effort

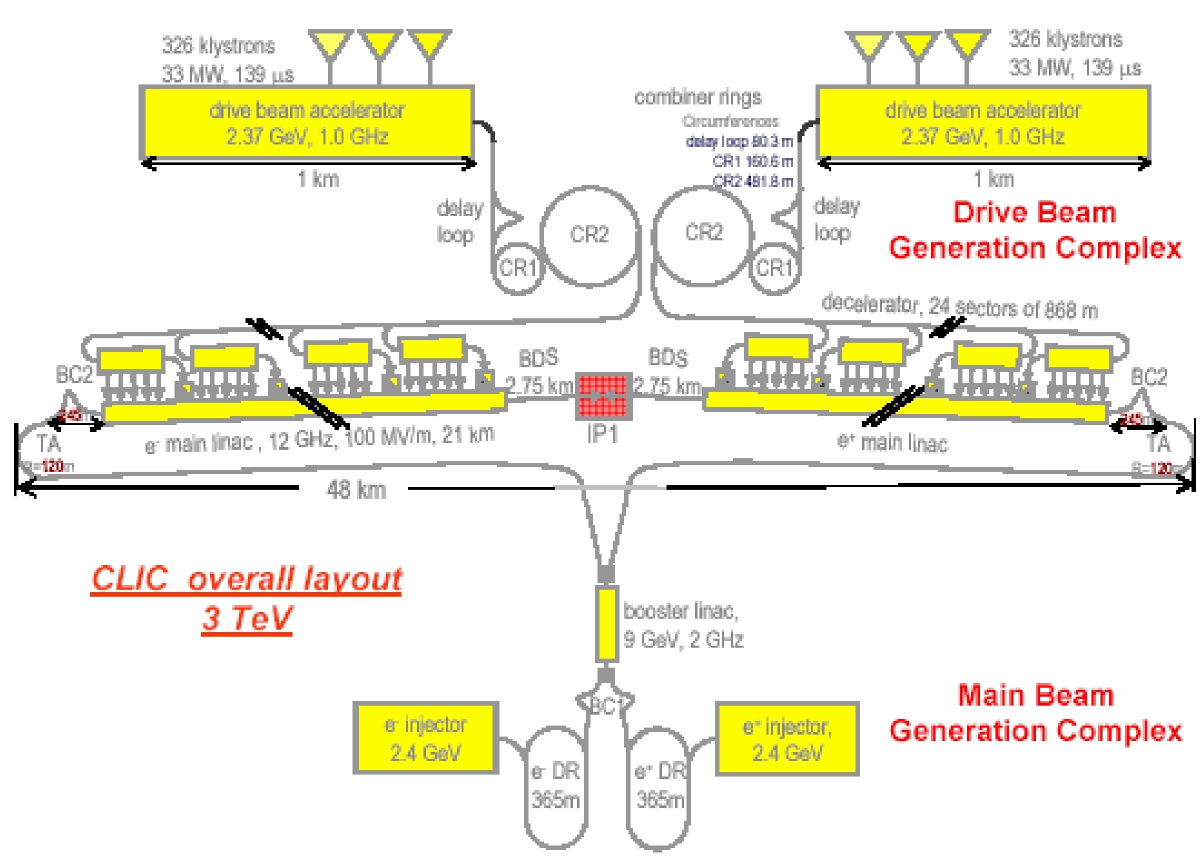
Rings patterned after ILC DR design; would reuse many PEP-II components





CLIC Layout

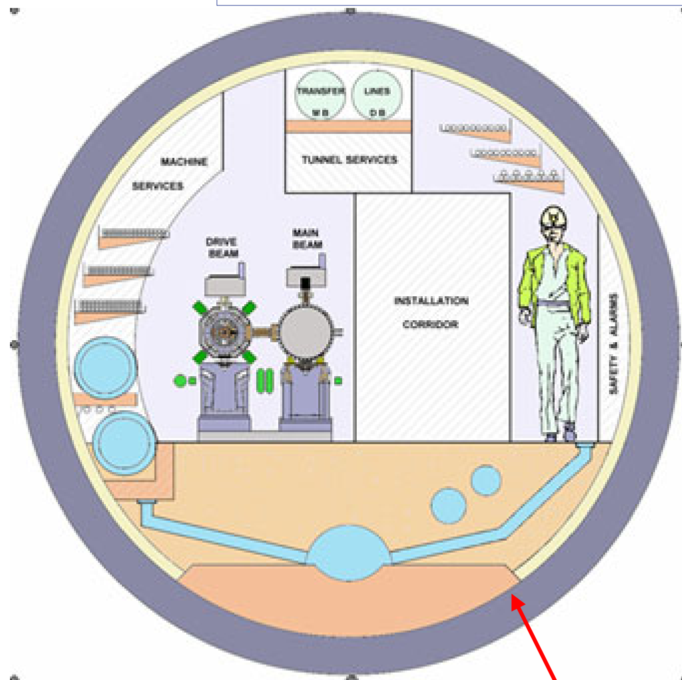
- **CLIC is designed for a 3 TeV collision energy**
  - has comparable *E* reach to LHC
    - uses "drive beam" for RF power generation



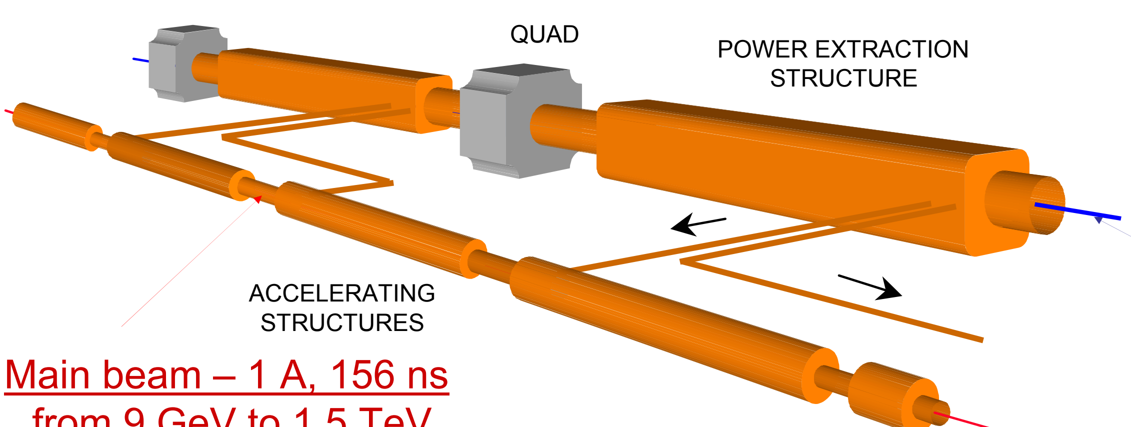
CLIC Features

- **Novel two-beam acceleration concept**
  - **efficient, reliable, cost-effective**
    - **no active elements in main tunnel**
  - **modular; easily upgradeable to higher energies**
  - **high gradients (>100 MV/m)**
  - **"compact" for 3 TeV linear machine (cf. ILC)**

CLIC TUNNEL CROSS-SECTION



4.5 m diameter



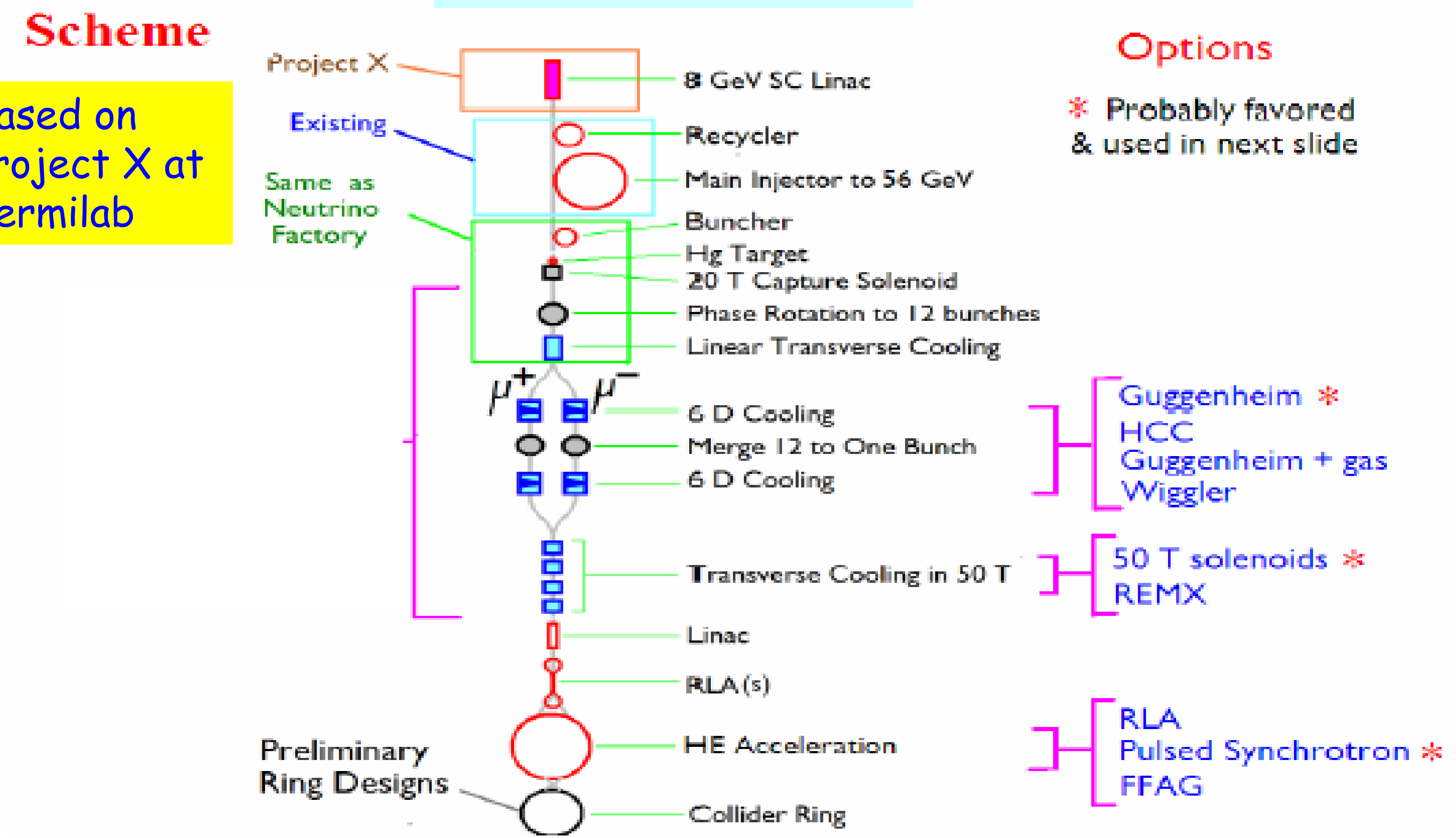
Main beam – 1 A, 156 ns
from 9 GeV to 1.5 TeV
100 MV/m

Drive beam - 95 A, 240 ns
from 2.4 GeV to 240 MeV

Muon Collider Scheme

Fits on Fermilab site

Based on Project X at Fermilab

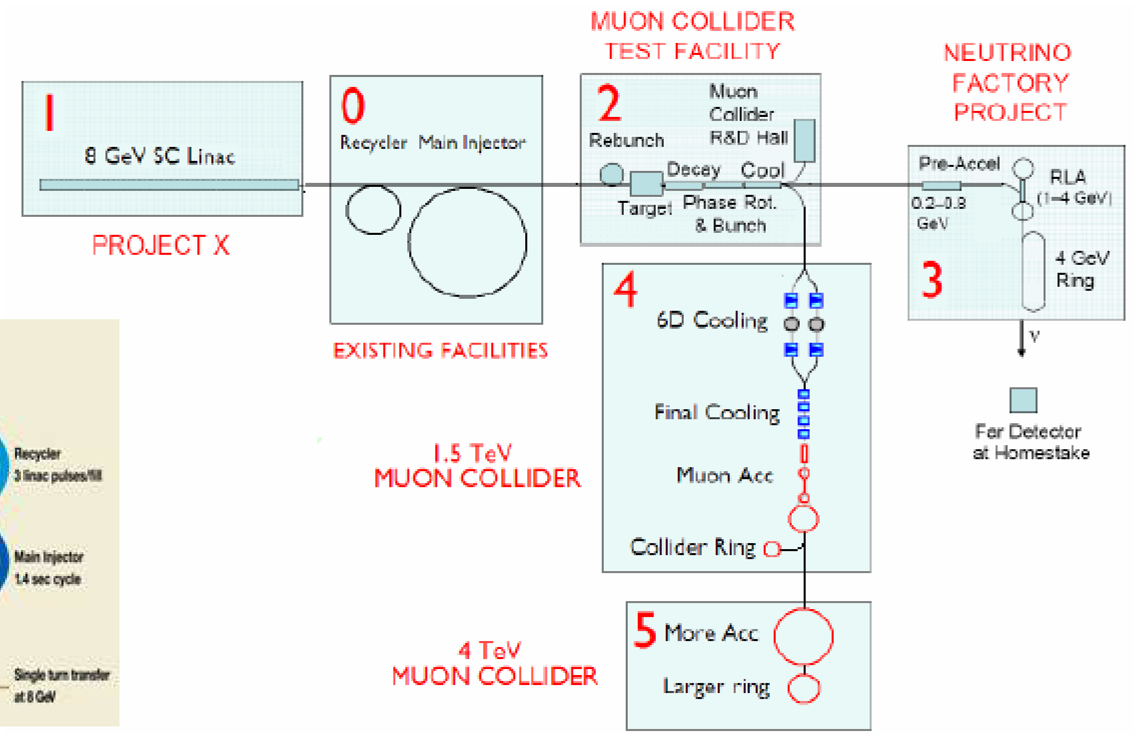


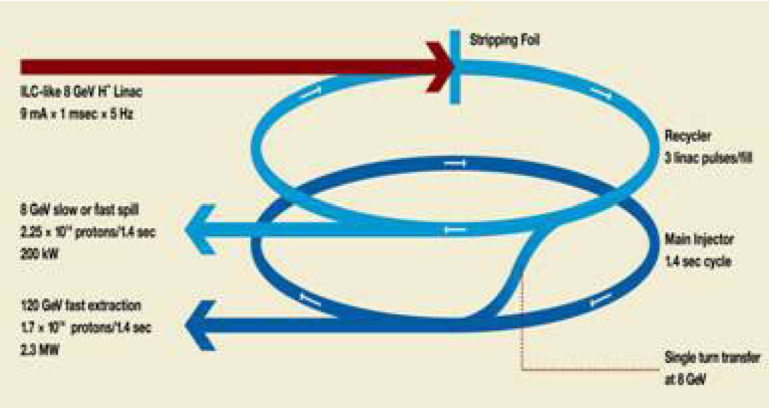
Phased Approach to Muon Facility

- **Fermilab exploring path toward future muon beam facility**
  - **"imperative" is to keep Fermilab (the only active U.S. HEP lab) scientifically productive in the era when Tevatron has been shut down**
    - **expected in approx. 2010**

Project X is the key!

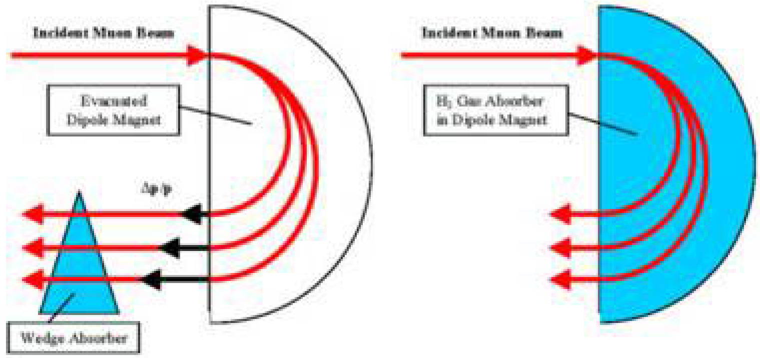
It also develops U.S. capabilities toward ILC





6D Cooling

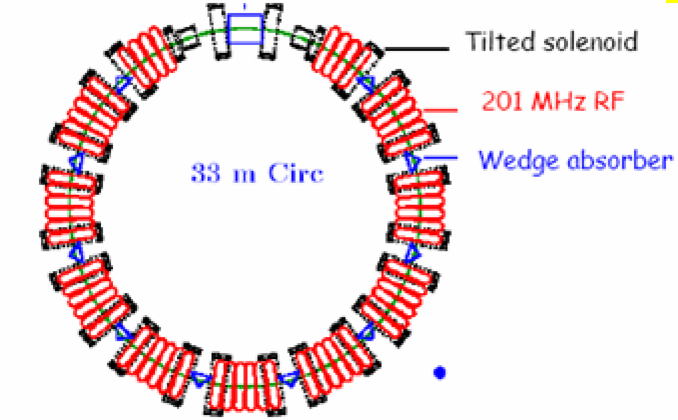
- For 6D cooling, add emittance exchange to the mix
  - increase energy loss for high-energy compared with low-energy muons
    - put wedge-shaped absorber in dispersive region
    - use extra path length in continuous absorber



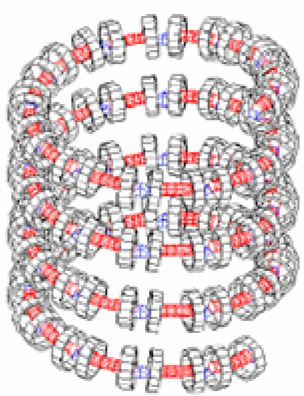
Gas-filled helical channel

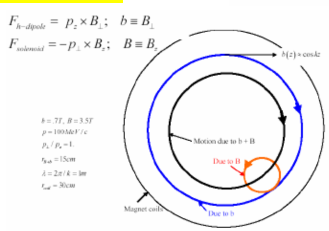
Issue: how to realistically incorporate RF into design

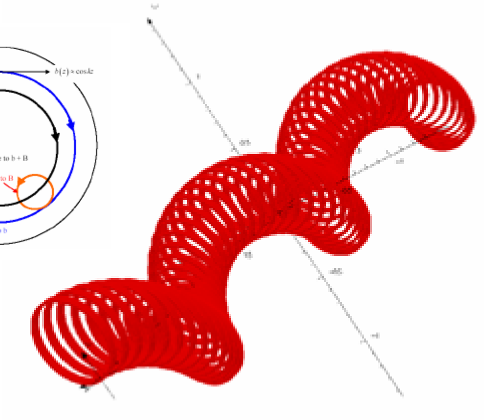
Cooling ring



"Guggenheim" channel







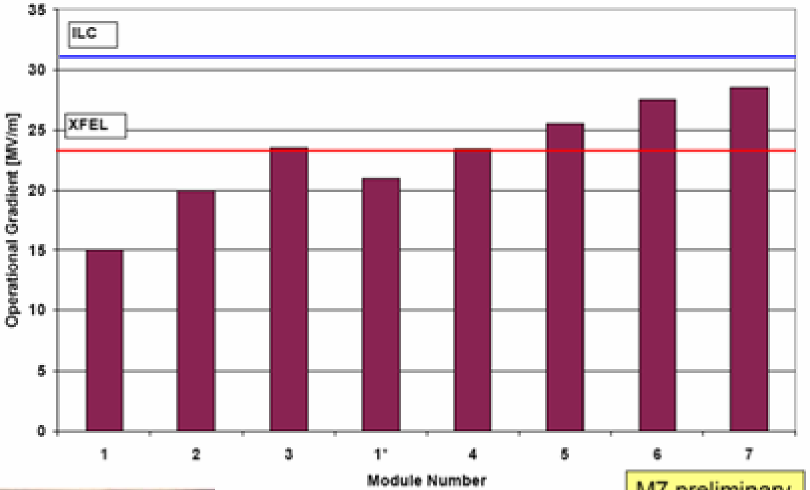
R&D Activities

- Putative projects covered here are embarked on R&D to:
  - prove physics concepts
  - validate technology choices
  - develop realistic, defensible cost estimates
- There are several "audiences" for the R&D results
  - the project advocates
  - the scientific community
  - ≥1 Laboratory directors
  - ≥1 funding agencies/governments
- Intensity and emittance will place high demands on instrumentation
- While I cannot do justice to the complete R&D programs, I will attempt to give a flavor of what is under way

ILC R&D Program (1)

- **Primary effort for ILC is reaching design gradient with production cryomodules**

Producing Cavities



M7 preliminary

Making progress; not there yet

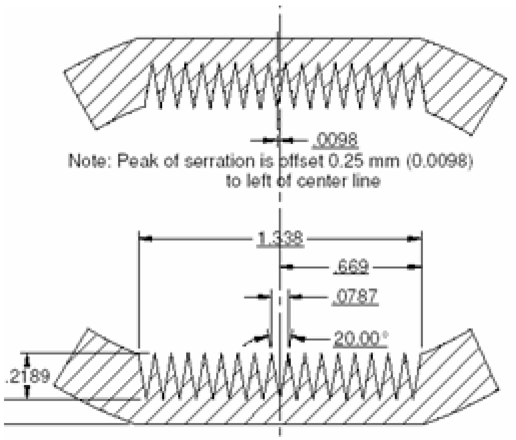
Cryomodule tests at DESY

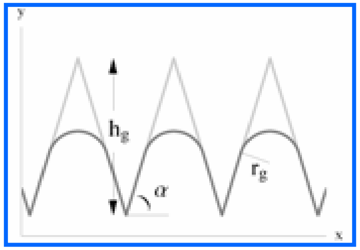
ILC R&D Program (2)

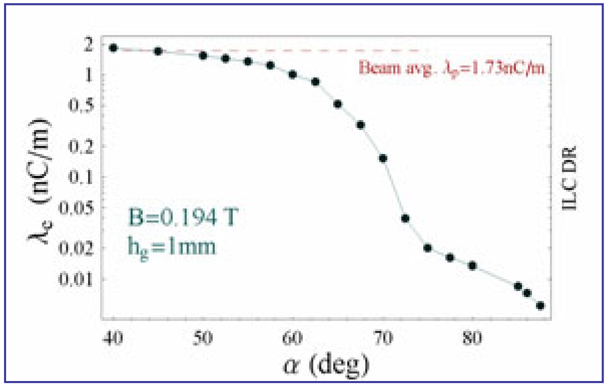
- **Another big technical concern is e-cloud effect in PDR**
  - issue is degradation of vertical emittance due to interaction with e-cloud

- **Initially addressed by simulations and tests of modified vacuum chamber designs at PEP-II**
  - testing "grooved" chambers and clearing electrodes
    - simulations indicate beneficial effects will keep DR parameters below instability threshold

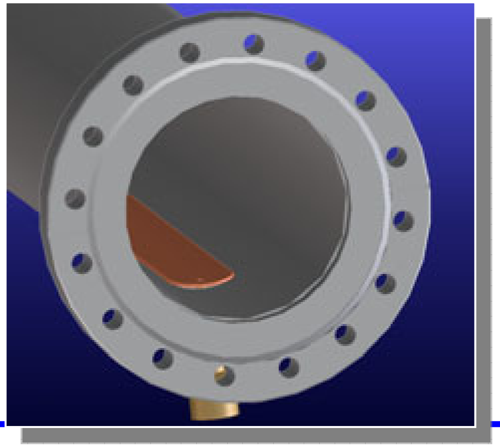
Grooved chamber







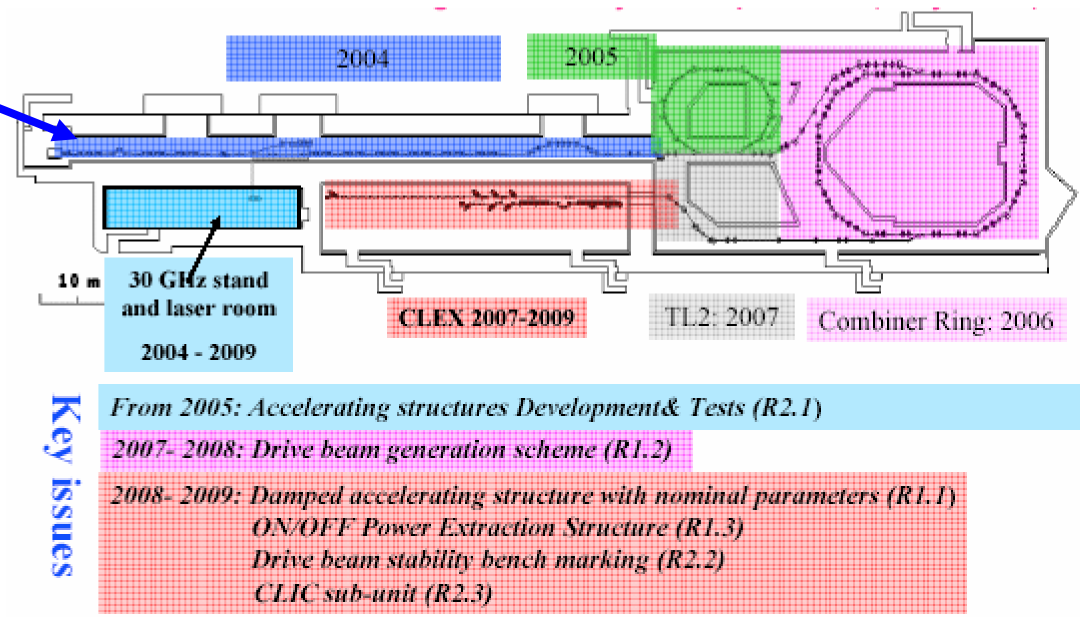
Clearing electrode chamber



CLIC R&D Program (1)

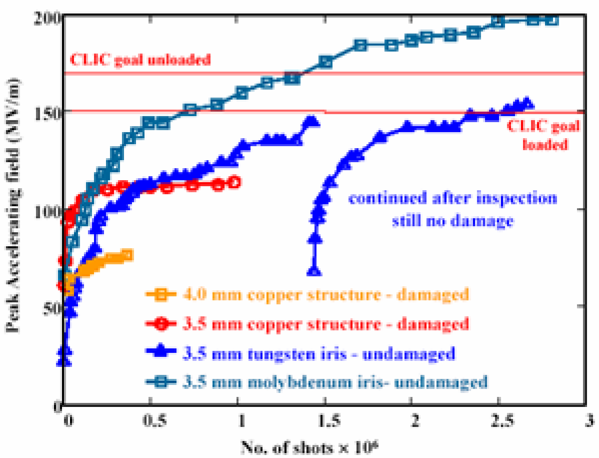
- Primary effort for CLIC is to demonstrate feasibility of CLIC technology (CTF3)
  - and estimate its cost
  - 19 countries currently involved in CLIC effort (centered at CERN)
    - coordination with ILC on issues of common interest, e.g., DRs

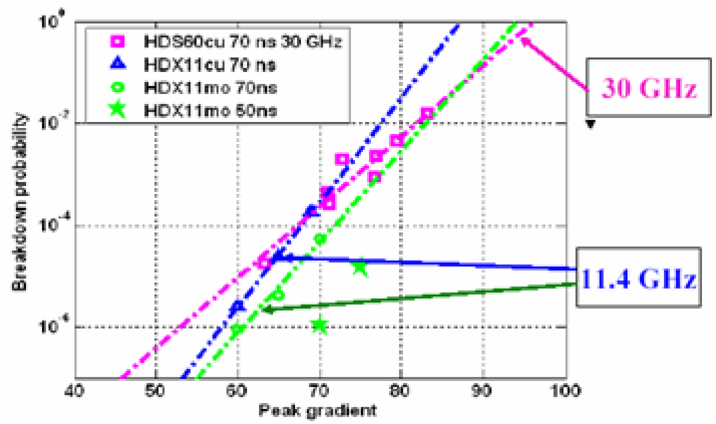
INJECTOR

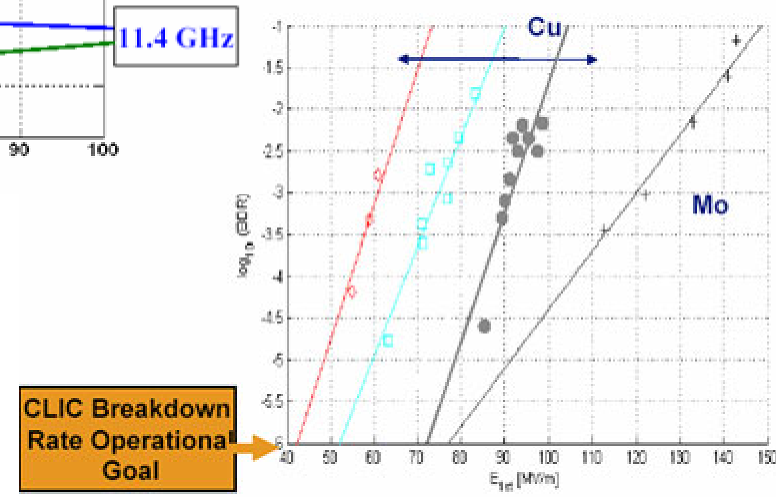


CLIC R&D Program (2)

- High gradients with "hard" materials demonstrated in CTF2
  - both Mo and W irises look workable (up to 190 MV/m!)
    - issue is breakdown rate, which is not yet acceptable for operation
      - breakdown criterion shows little frequency dependence



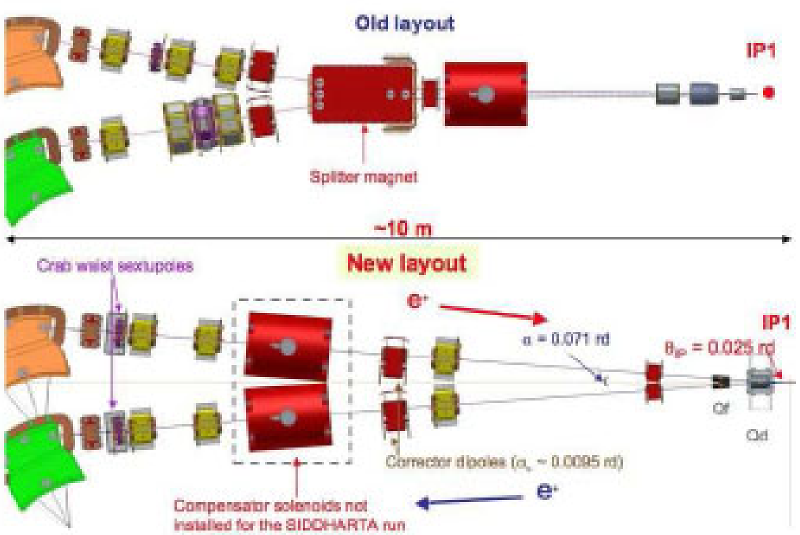


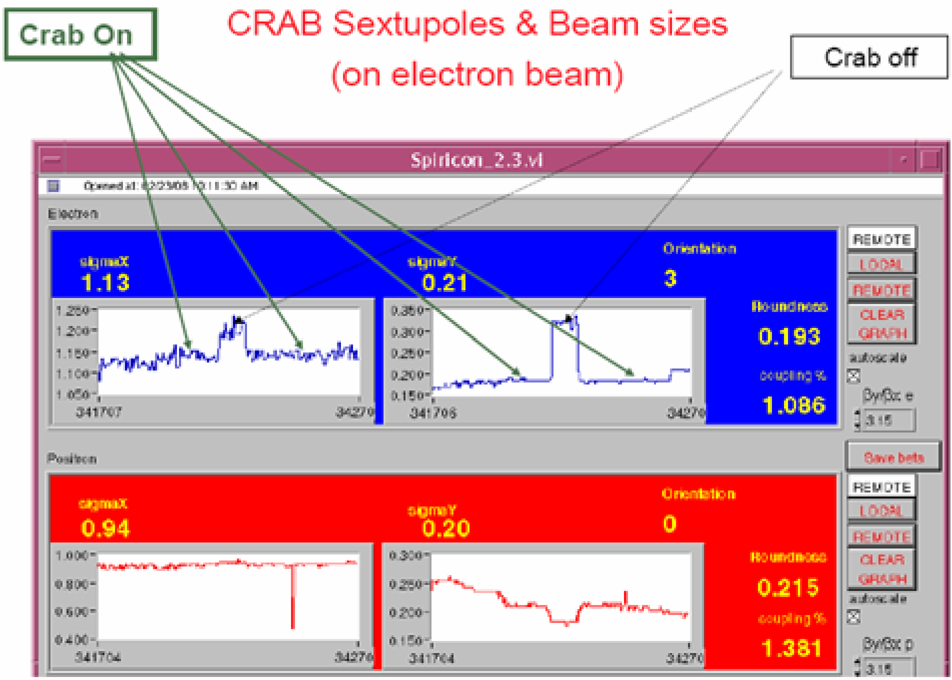


Super B Factory R&D

- **Primary issues**
  - does crab waist scheme work as expected?
  - can the IP beta value be low enough to get a x100 luminosity increase?

- **Test of crab waist scheme at DAΦNE getting under way**
  - modified IR to give crossing angle
    - sextupoles added to IR





Muon Beam R&D Program

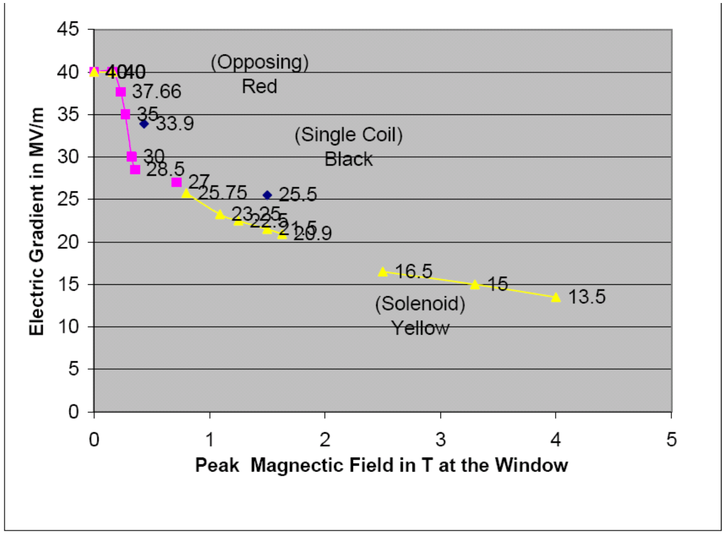
- Broad R&D program under way in all regions
  - Europe: various institutions sponsored by BENE and UKNF
  - Japan: NuFact-J group supported by university and some US-Japan funds
  - US: NFMCC program sponsored primarily by DOE with help from NSF
- Includes several international efforts already
  - MERIT (target test)
  - MICE (ionization cooling test)
  - EMMA (electron model of non-scaling FFAG)
  - IDS-NF (Neutrino Factory design study)
- Other experiments in planning stage
  - MANX (6D cooling)
  - Target test facility at CERN

Note: R&D effort relevant both to NF and MC

Cooling Channel RF

- Cooling channel requires high-gradient 201 MHz RF in a strong (solenoidal) magnetic field
  - prototype cavity built by LBNL-Jlab collaboration (Li, Rimmer, Virostek)
    - easily reached 19 MV/m design gradient without magnetic field at MTA
    - waiting for a Coupling Coil to test in high magnetic field

- 805 MHz experiments indicate substantial degradation of gradient in such conditions

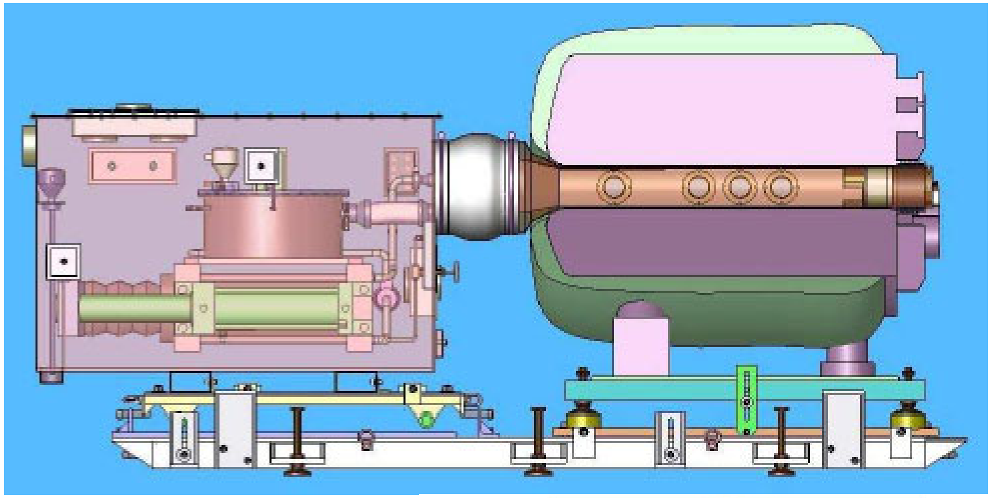


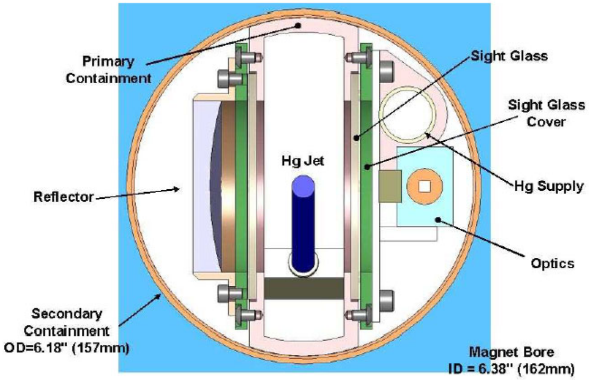
MERIT

- MERIT experiment tested Hg jet in 15-T solenoid (Kirk, McDonald, Efthymiopoulos)
  - 24 GeV proton beam from CERN PS
    - completed October 2007

P_{beam} beyond 4 MW is feasible

15-T solenoid and Hg jet installed in TT2A tunnel at CERN





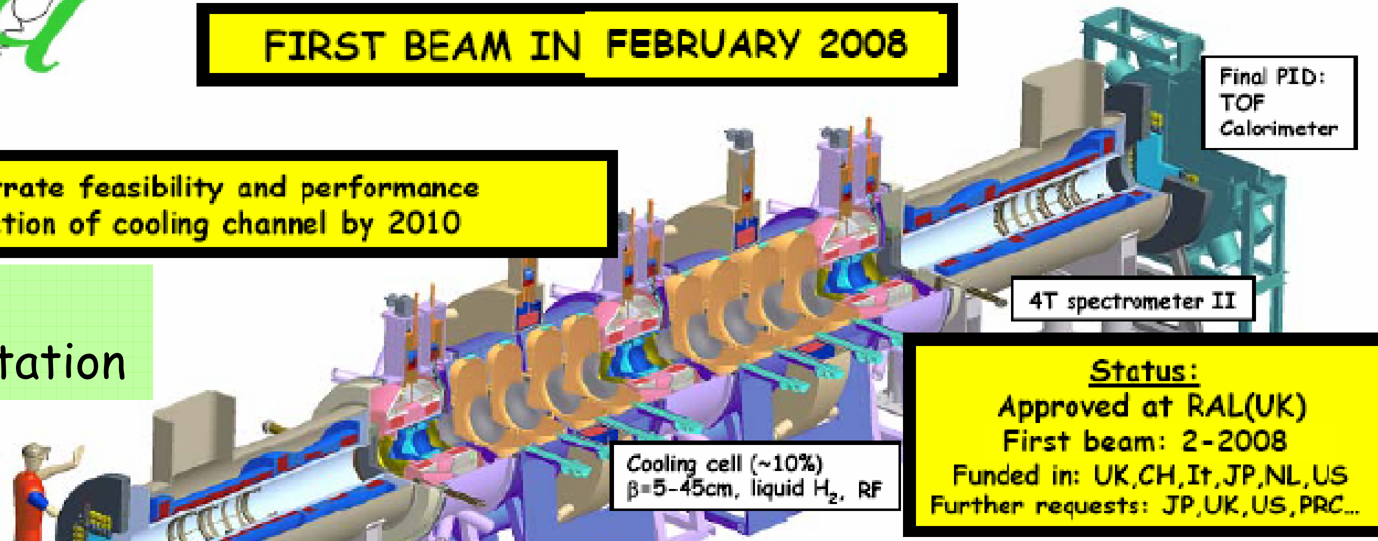
MICE

Muon Ionization Cooling Experiment

FIRST BEAM IN FEBRUARY 2008

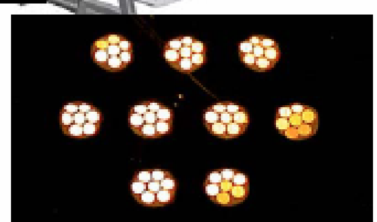
Demonstrate feasibility and performance of a section of cooling channel by 2010

Simple concept...
complicated implementation



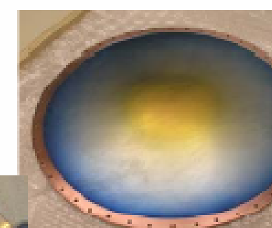
Status:
Approved at RAL(UK)
First beam: 2-2008
Funded in: UK,CH,It,JP,NL,US
Further requests: JP,UK,US,PRC...

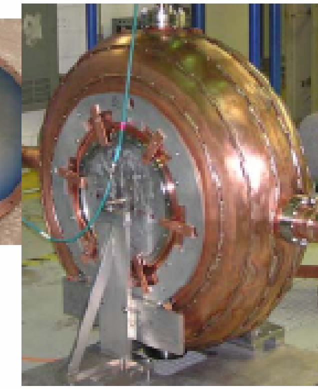
Prototyping:



Scintillating-fiber tracker

Liquid-hydrogen absorbers





200MHz RF cavity with beryllium windows

Challenges:
RF in magnetic field
Proximity of RF and LH_2

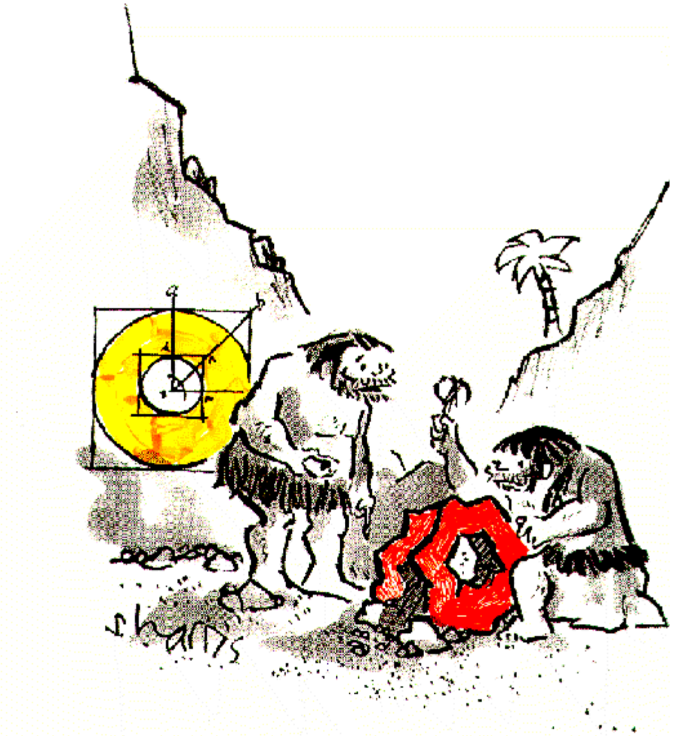
Summary

- Facilities now in the planning stage offer great potential to address the key outstanding questions in HEP
  - origins of mass
  - origin of matter-dominated universe
- R&D toward design of these new HEP facilities progressing on many fronts
  - from U.S. perspective, Project X is key to maintaining future options
- As with all accelerator R&D, success depends on synergy between accelerator physics and accelerator technology
  - in particular, control of instabilities and emittance will require state-of the-art diagnostics (to ensure "blame" goes to the right group ☺)
- The skills of the instrumentation builders will be critical in turning accelerator physicists' dreams into the cutting-edge scientific tools of the future

Final Thought

- **Challenges of a future accelerator complex go well beyond those of today's beams**
  - **developing solutions requires substantial R&D effort to specify**
    - **expected performance, technical feasibility/risk, cost (matters!)**

Critical to do experiments and build components.
Paper studies are not enough!



"I guess there'll always be a gap between science and technology."